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New quantum dot transistor

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Abstract. Modulation doped N-AlGaAs/GaAs/InAs/GaAs/InAs/GaAs-heterostructures with InAs-quantum dots in device channel have been grown and investigated. Their photoluminescence spectra and electrical transport properties both in low and high electric fields were studied. Using these structures, modulation doped FET's have been fabricated and analyzed. It was demonstrated that the quantum dot FET's present the new type of the hot electron devices, promising for high speed applications.

Introduction

Recently it has become possible to fabricate laterally defined nanostructures, such as quantum dots (QD's). Properties of zero-dimensional electrons confined in such structures attract a great interest both in physics and device applications. The most promising nanometer (nm)-scale QD-structures are formed by the Stranski–Krastanow mode of the heteroepitaxial growth in which a material is deposited on a lattice mismatched substrate beyond some critical thickness to form very small dot structures (~ 20 nm) [1–3]. Although much work has been done on the structural and optical properties of QD's, relatively little is known on the influence of the dot-induced potentials on transport of electrons flowing in the neighborhood of dots, particularly, in very high electric field, and on the operation of the real QD-modulation doped field effect transistors (QD-MODFET's). In this work, we study the optical and electrical transport properties of the two dimensional (2D) electrons in the modulation doped N-AlGaAs/GaAs-heterostructures with the InAs-dots embedded in the GaAs-channel, and analyze the characteristics of QD-MODFET's fabricated on their basis. It was shown that mobility μ_{2D} and concentration n_{2D} of electrons are strongly influenced by the presence of QD's. The high field I–V-characteristics (I–V–C's) of MODFET's exhibit the contributions both from mobile 2D-electrons and the electrons localized in QD's. QD-devices demonstrate the new type of the hot electron transistors which can be promising for high speed applications.

1. MBE growth of QD MODFET-structures

The of QD-MODFET-structures (S1) studied here have been grown by molecular beam epitaxy (MBE) on (100)-semi insulating GaAs-substrates. Figure 1 shows schematically their cross sections. First we grew a $0.5\text{-}\mu\text{m}$ -thick undoped GaAs-buffer layer and two very thin InAs-layers, separated by the undoped GaAs spacer layer. Thickness of each InAs layer was 1.07 nm and thickness of the GaAs spacer layer was 5.6 nm. Two layers of QD's with respective size and density were formed. Then, after growth of the second GaAs-spacer layer with thickness of 5.6 nm, the 10 nm-thick undoped $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ spacer layer, a $2.5 \times 10^{12} \text{ cm}^{-2}$ Si δ -doped layer and a 35 nm-thick undoped $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ barrier layer were grown. The QD-MODFET-structures were completed by the 6 nm-thick undoped GaAs layer and the 40 nm-thick $3 \times 10^{18} \text{ cm}^{-3}$ Si-doped GaAs contact layer. Figure 2

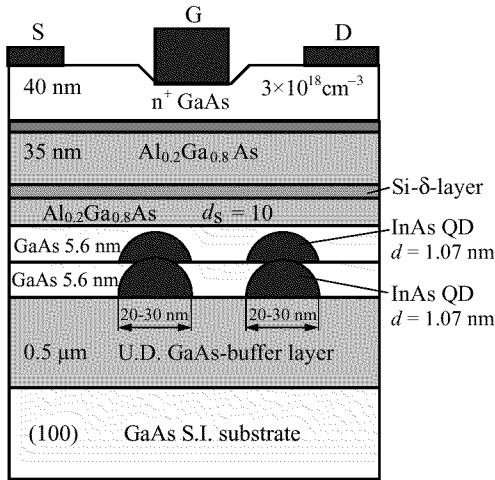


Fig. 1. Cross section of QD-MODFET structure.

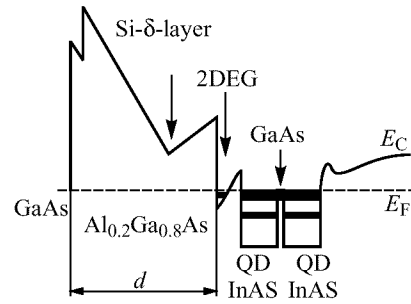


Fig. 2. Band diagram of QD-MODFET structure.

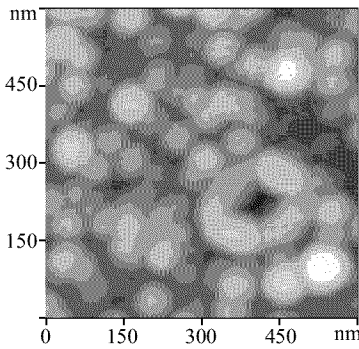


Fig. 3. AFM-photograph of sample S1.

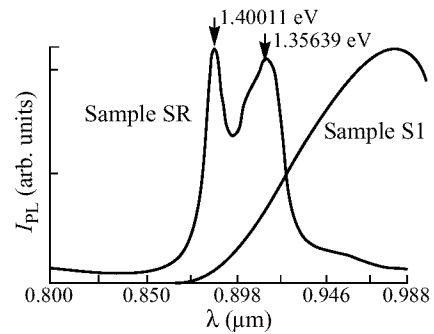


Fig. 4. PL-spectra of samples S1, SR.

depicts the energy diagram of the above QD-MODFET-structures. As a reference sample (SR), we also grew the pseudomorphic-MODFET-structure without QD's with the same average $\text{In}_{0.17}\text{Ga}_{0.83}\text{As}$ composition of the 12 nm-thick channel layer.

2. Optical and low field electrical properties of QD-MODFET-structures

Figure 3 shows AFM-photograph of the sample S1, in a case of which the MBE-growth was completed immediately after growing the second InAs layer. According to this figure, the average size of QD's and their areal density are ~ 40 nm and $3 \times 10^{10} \text{ cm}^{-2}$, respectively.

In Fig. 4 PL-spectra of the different samples, measured at 77 K, are presented. Two PL peaks in the sample SR, typical of the modulation doped quantum wells [4], correspond to the optical transitions between the two populated electron subbands and the hole subbands. On the other hand, the broad PL-bands in samples S1 correspond to the InAs-QD's. In Table 1 the results of the Hall effect measurements of electron mobility μ_{2D} and electron concentration n_{2D} of samples S1 and SR are presented. As seen, the insertion of QD's into the device channel results in the reduction of μ_e and the essential reduction of n_{2D} in sample S1. In the latter case, obviously, the trap of majority of electrons by QD's takes place. The low values of electron mobilities in sample S1 as compared with sample SR, are

Table 1. Results of the Hall effect measurements of μ_{2D} and n_{2D} .

Samples	μ_{2D} (cm ² /V s)		n_{2D} (cm ⁻²)	
	77 K	300 K	77 K	300 K
SR	10108	4500	8.2×10^{11}	9×10^{11}
S1	3000	2852	1×10^{11}	6×10^{10}

the direct indication, that insertion of InAs-QD’s gives rise the specific random potentials, which scatter 2D-electrons very effectively. The charges of electrons trapped by QD’s and the effects of strain around each QD can be responsible for these potentials.

3. High field electric transport in QD-MODFET-structures

Because the essential part of electrons in samples S1 are trapped by QD’s, they can not participate in the low field electric transport. However, their contributions can be displayed at high electric fields. For such experiments, special MODFET’s with a the 2 μ m-drain-to-source spacing, without gate and with different widths of the ohmic contacts have been fabricated. Their I–V–C’s are shown in Fig. 5. As seen from this figure, in contrast to “standard” FET’s, they have the anomalous “two-step” shape (instead of the conventional curve with “saturation”). When the distance between the sample surface and the channel is reduced by means of etching, the first current step is reduced or even completely disappeared, and I–V–C becomes of the threshold type, due to presence of second step only. The two current steps are explained by the contributions from two types of electron states: the mobile 2D-electrons (as in “standard” FET) responsible for the first step, and the electrons localized in QD’s. The second ones, responsible for the second step, give the contribution only at the high electric field F , above some threshold value, as a result of the field induced electron emission from QD’s. The reduction of the current at the first step, after the additional surface etching (the surface field induced depletion) supports our interpretation of this part of I–V–C.

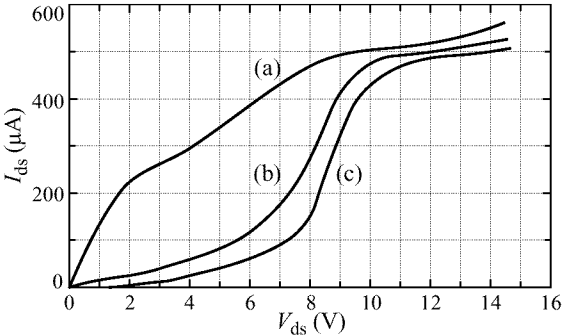


Fig. 5. I–V-characteristics of QD-MODFET structures: (a)—before etching, (b) and (c)—after additional surface etching.

4. QD-MODFET

Using the structures S1, MODFET’s with gate length of 0.4 μ m have been fabricated. The I–V–C’s of these QD-MODFET’s are shown in Fig. 6. As seen from this figure applying even the zero-bias to the gate leads to the essential shift of the second current step to the lower voltages as compared with the “ungated” devices. This effect can be explained by

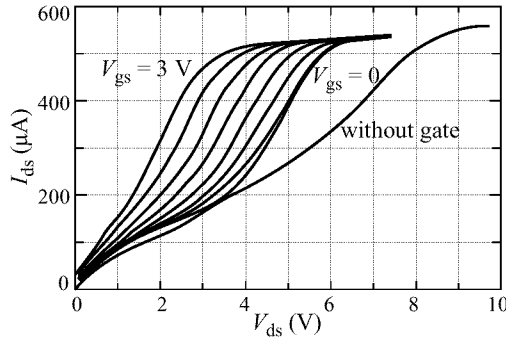


Fig. 6. I–V-characteristics of QD-MODFET structures for different values of V_g (step is -0.5 V).

the redistribution and increasing the peak value of electric field in the device channel under influence of gate voltage U_G . As seen from Fig. 6, the saturation current I_{dss} for the second step practically does not depend on the gate bias U_G . However, its threshold voltage U_{th} is very effectively influenced by negative values of U_G . This result is principally different from the behaviour of the “classical” FET, for which only the electron density and, respectively, I_{dss} are influenced by U_G . These results show, that in a case of QD-MODFET’s, the concentration of electrons participated in the current flow, becomes independent on U_G , but threshold voltage U_{th} , for initiation of the electron emission from QD’s, is reduced, when U_G becomes more negative. This reduction of U_{th} is explained by increasing the effective electric field in the d_{GD} -spacing. The threshold field, which is determined by the energy of electron states in QD’s, can be evaluated from the I–V–C’s of the “ungated” MODFET: $E_{th} = 4 \text{ V } \mu\text{m}^{-1}$. Proceeding from the effect of electron emission from QD’s, we have evaluated the depth of the energy levels EQD in QD’s: $E_{QD} = eE_{th}d_{QD} = 160 \text{ meV}$, where $d_{QD} = 40 \text{ nm}$ is the lateral size of QD’s. The important result of this study is the finding of the sufficiently high value of the transconductance $g_m \cong 500 \text{ mS/mm}$ at the very small expected effective device capacitance.

5. Conclusion

New QD-MODFET has been demonstrated. Operation of the QD-MODFET is principally different from that of conventional (“classical”) FET, in which U_G carries out the function of the modulation of the thickness of the conducting channel. On the other hand, in QD-MODFET, at small electric fields, we have not free electrons in device channel, because they are localized in QD’s. At high electric field FDS in QD-MODFET, U_G -potential controls the electron emission from QD’s, resulting in a new shape of I–V–C’s. The operation of such a transistor reminds that of the vacuum triod, where, the gate electrode, similar to the grid electrode in vacuum triod, controls the electron emission from their source-QD’s.

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